NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

SUCCESSFUL STRATEGIES FOR ACHIEVING RELIABILITY REQUIREMENTS IN WEAPON SYSTEMS ACQUISITION

by

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March 2002

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13. ABSTRACT *(maximum 200 words)*

Reducing the logistics burden is a current focus for the Army as it works to develop and field the Objective Force. Increasing reliability is a proven way to achieve this goal, with an added benefit of reducing O&S costs and increasing the effectiveness of the soldiers.

Many programs have had difficulty achieving their required reliability. Operational Testing data gathered by the Army Test and Evaluation Command indicates a decreasing trend in achieving reliability requirements with more than 80% failing to achieve requirements. It is intuitive that it would be even more difficult to achieve ultra-reliability, a higher level of reliability and a proposed goal of the Future Combat Systems Program.

To determine what successful practices should be used to achieve reliability requirements, we should look to successful programs to show us the way. To that end, this exploratory study questions successful Army programs for practices, recommendations, and lessons learned, that could be shared with other programs to achieve reliability requirements.

If we are unsuccessful in our endeavors to improve reliability achievement, future forces will be unnecessarily burdened by our mistakes and incapable of progress to achieving the Objective Force.

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SUCCESSFUL STRATEGIES FOR ACHIEVING RELIABILITY REQUIREMENTS IN WEAPON SYSTEMS ACQUISITION

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I. INTRODUCTION

A. PURPOSE

This research focuses on reliability aspects of the Future Combat Systems (FCS) and analyzes the strategies that were used to achieve it. This research is applicable to other weapon system programs, especially those where the goal is to reduce the logistics burden by developing and fielding a reliable system.

B. BACKGOUND

The U.S. Army, as well as the other services, has been plagued with a large logistics burden. The principle logistics burdens are the fuel, ammunition, food, water, and spare parts necessary to sustain an operational military force. Because of uncertainties in combat, plans for stockpiles of supplies are designed to meet any contingency. As a result, large amounts of supplies and logistics personnel are moved into theater to support the combat troops and equipment on a just-in-case basis. [Ref. 1:p. 26]

It is anticipated, future forces will be called upon to be inserted into the combat zone by air, and must be prepared to accomplish a numerous variety of combat missions, operating for up to 14-days without logistics support from outside the battle area. Because of this requirement, future forces and systems must require less logistical support than their predecessors. [Ref. 1:p. 27]

Reliability is considered a key focus for the reduction of the logistics burden. Reliability is defined as the

> probability that an item will perform its intended function for a specified interval under stated conditions. [Ref. 2:p. 36]

With more reliable systems, less spares and maintenance assets would be required for support, thereby reducing the logistics burden.

The Army is focused on reducing the logistics burden of currently fielded systems and future systems under development. One of these, the Future Combat Systems (FCS) is a weapon system currently under development as part of the Army's Objective Force. The FCS may consist of as many as five separate robotic systems that interface together through a central manned command and control vehicle. Because of its autonomous function, the FCS must achieve high reliability. To this end, the Army Science Board recommended in a study that the FCS establish ultra-reliability as a Key Performance Parameter (KPP).

Many programs have had difficulty achieving their required reliability. It is intuitive that it would be even more difficult to achieve ultra-reliability, a higher level of reliability. Operational Testing data gathered by the Army Test and Evaluation Command depicts that during the period of 1985 to 1990 41% of systems met reliability requirements. This figure worsened to 20% meeting reliability requirements during the period of 1996 to 2000. Worse yet, those that failed to meet reliability requirements also failed to meet even 50% of the reliability goals. [Ref. 3]

Because many programs were unable to achieve reliability requirements, LTG Kern, the Military Deputy to

the Assistant Secretary of the Army for Acquisition, Logistics, and Technology, initiated a study to determine what should be done to remedy the situation.

C. RESEARCH QUESTIONS

1. Primary Research Question

What strategies should be used to achieve reliability requirements for weapon system development?

2. Secondary Research Questions

a. What is reliability and how does it affect total life cycle costs and the logistics burden?

b. Why is ultra-reliability a recommended goal for the FCS program?

c. Should ultra-reliability be a goal of weapon system programs?

d. What is the guidance for achieving reliability requirements?

e. How have successful weapon system programs achieved reliability requirements?

i. How did programs organize to achieve reliability requirements?

ii. How were reliability requirements developed?

iii. What management plans for achieving reliability requirements were developed and implemented?

iv. What processes were used to achieve reliability requirements and how was this measured?

v. Where in the Acquisition Process was the program focused on achievement of reliability requirements?

f. What are the best strategies that should be used for the FCS program as well as other weapon system programs?

D. SCOPE

The scope of the study will include: (1) an in-depth analysis of the logistics burden and the effect of reliability upon it; (2) identification and analysis of the acquisition lifecycle for reliability inputs; (3) identification and interviews of successful programs to identify their focus on reliability; (4) review of advantages and disadvantages of the approaches used by the programs. The thesis will conclude with a recommendation for strategies focusing on improving reliability for the Future Combat Systems and other weapon system programs.

E. METHODOLOGY

The methodology utilized in this thesis research is the following:

1. Conduct a literature search of books, magazine articles, CD-ROM systems, and other library information.

2. Conduct an Internet search of data pertaining to the Future Combat Systems, reliability, and reliability guidance.

3. Identify the reliability requirements of the Future Combat Systems.

4. Utilize Director of Combat Development (DCD), Training and Doctrine Command (TRADOC), and Army Test and Evaluation Command (ATEC) reliability experts.

5. Utilize ATEC Operational Test Data to identify programs that successfully met reliability requirements.

6. Develop interview questions to obtain data to answer the primary and secondary research questions.

7. Question those successful programs for strategies for the achievement of reliability requirements.

8. Evaluate the methodologies by analyzing the data.

9. Compare responses to literature review and one another.

10. Formulate recommendations based on the analysis of the thesis.

F. ORGANIZATION

Chapter I. *Introduction*. This chapter presents the problem of the logistics burden and the reliability component impact. It also outlines the FCS and its goal of reducing the logistics burden. The remainder of the thesis organization is outlined below.

Chapter II. *Reliability, Its Effects, and Guidance for the Achievement of Requirements*. This chapter provides the background of reliability by defining and describing reliability and its effects on the logistics burden and lifecycle costs. It also outlines both mandatory and discretionary guidance for the achievement of reliability requirements.

Chapter III. *Methodology*. This chapter outlines the methodology of the interviews. It identifies how the interviews occurred, the interview subjects, and the questions posed.

Chapter IV. *Data Summary*. In this chapter, the subject's responses to the interview questions are summarized.

Chapter V. *Data Analysis*. Data, in the form of interview responses, is analyzed to discover trends which are then compared to published guidance. Responses are also analyzed to identify advantages and disadvantages.

Chapter VI. *Conclusions and Recommendations*. This chapter restates the primary and secondary research questions, summarizes the findings, and makes recommendations for implementation.

G. BENEFITS

The achievement of reliability requirements is a problem that is currently being studied by the Army due to the inability of many programs to achieve reliability requirements. This study will review the importance of reliability and its effect on the logistics burden and a program's life cycle costs. It will also examine what guidance exists and what strategies successful programs are using to achieve reliability requirements. The study will conclude with recommendations of successful strategies to achieve reliability requirements for use by the FCS and all weapon system programs.

II. RELIABILITY, ITS EFFECTS, AND GUIDANCE FOR THE ACHIEVEMENT OF REQUIREMENTS

A. INTRODUCTION

The Army, in attempting to field its Objective Force – the force of the future – has focused its efforts on reducing the logistics burden. One prescribed method for achieving this is to make systems under development more reliable. Systems that are reliable have fewer failures, require less maintenance and spares, and have greater availability. Because of this, reliability can act as a combat multiplier and also have a profound effect on the reduction of the logistics burden and life cycle costs.

Few acquisition programs have achieved reliability requirements in the last decade. Failure to achieve these requirements can result in the fielding of a system that is not operationally suitable, delay of fielding to correct deficiencies, or cancellation of the program.

The Future Combat Systems (FCS) Program, in the early stages of development, will attempt to develop a highly reliable combat system. The goal is to field a system with a reduced logistics burden, benefiting the Army by requiring less logistics support than currently fielded systems.

This chapter provides an overview of reliability and its effects on the logistics burden and lifecycle costs, introduces the FCS and its reliability requirements, and outlines reliability guidance and where reliability is encountered in the acquisition life cycle.

B. RELIABILTY AND ITS EFFECTS ON THE LOGISTICS BURDEN AND LIFE CYCLE COSTS

1. Introduction to Reliability

The most widely used definition of reliability is the

> probability that an item will perform its intended function for a specified interval under stated conditions. [Ref. 2:p. 36]

The military once had its own definition of reliability, which it defined in Military Standard (MIL-STD) 721-C, *Definitions of Terms for Reliability and Maintainability*, but chose to cancel it.

In weapon system documents, the military also uses terms such as mission reliability and a new concept, ultra-reliability. Mission reliability is often defined as "the probability that a system will perform mission-essential functions for a period of time under conditions stated in the mission profile." [Ref. 4: p. 10-3] It is commonly accepted that ultra-reliability is an exceptionally high reliability, with an extremely large Mean Time Between Failure. The National Aeronautic Space Administration (NASA) refers to ultra-reliability in software as having a failure probability during a one-hour test mission of less than 0.0000001. This means that the software will not fail 99.99999% of the time. [Ref. 5]

Reliability probabilities for various components can be modeled using different reliability distributions, depending upon their characteristics. The two most common are the exponential distribution and the Weibull distribution. The exponential distribution, the simplest to model, describes reliability failures in systems such as

for electronics, which exhibit a constant failure rate. The exponential reliability distribution is expressed as:

$$R(t) = e^{-\lambda t}$$

where R is the reliability, t is time, and λ is 1/Mean Time Between Failure (MTBF). [Ref. 2:p. 39] MTBF is the mean time that a system will successfully perform its function before failing and is usually expressed in hours. Reliability is therefore an exponential distribution that is a function of MTBF and time, and as time increases, reliability decreases. It can therefore be seen that MTBF is a key parameter of reliability.

If in the above equation the MTBF was 1000 hours, λ would be 1/1000 or 0.001 and the resulting reliability after 100 hours is predicted by the exponential reliability distribution to be about 0.90. This means that after 100 hours of operation, 90% of the time the item will still be operational. After 1000 hours, the reliability would be about 0.36, or 36% of the time it will be operational.

System reliability is dependent upon the reliability of the system's subcomponents and the way they are connected. There are two primary ways of connecting subcomponents, these are in series and parallel. Series connection is most common, with parallel connection of critical components to provide redundancy and therefore, increased reliability. [Ref. 2:p. 41] In the figure below, even though the subcomponents in series connection have a higher reliability than the two connected in parallel, the overall system reliability for those in series is less than for those in parallel.

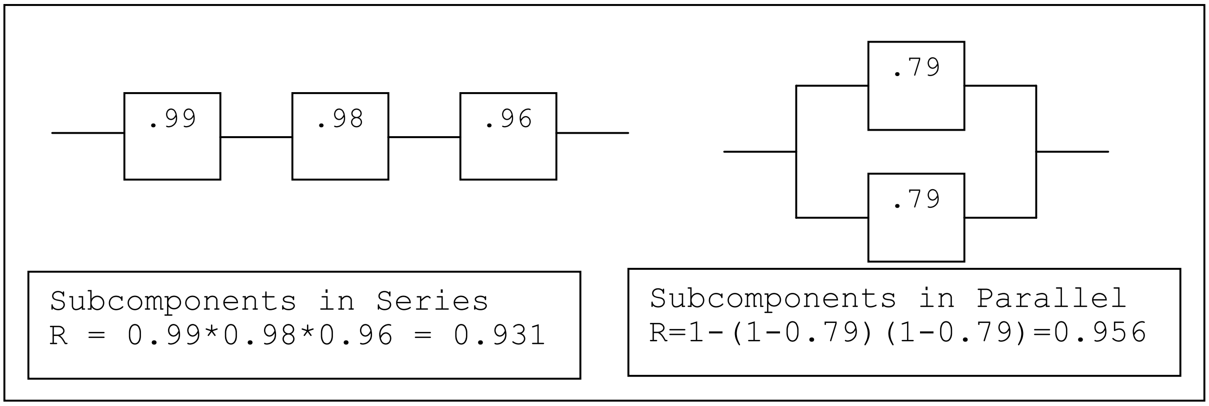

Figure 1. Series vs. Parallel Design

To determine the reliability of a system, the individual reliability of the subcomponents in series are multiplied together, while for those in parallel, the subcomponent unreliabilities (1-R) are multiplied together and the unreliability is taken again (1-(1-R)), resulting in the predicted reliability. [Ref. 6:p. 32] The reliability of a system with subcomponents in series can be no greater than the reliability of the least reliable component. The reliability of a system can be improved by placing components in parallel. This increases the reliability because if one component fails, the other component, as well as the system, will continue operating.

The design of equipment and weapon systems has increased in complexity over time, which may also reduce reliability. Take for example table one, a tractor that only had 1,200 critical parts in 1935 now may have more than 2,900 critical parts. This reduces the tractor's reliability from 88.7% in 1935 to 74.8%, assuming an average component reliability of 99.99% and critical components arrayed in series. Worse yet, this translates to more than twice the number of tractors failing per 1,000 tractors now as compared to 1935. A similar prediction may

be made when comparing military weapon systems such as the M4A1 Sherman tank with the M1A2 Abrams tank.

Farm tractor model year	Number of critical components	Tractor reliability per year,* assuming an average component reliability of 99.99%	No. of tractors failing per year per 1,000 tractors
1935	1,200	88.7%	113
1960	2,250	79.9%	201
1970	2,400	78.7%	213
1980	2,600	77.1%	229
1990	2,900	74.8%	252
*It is assumed that all critical components are reliabilitywise in series.			

Table 1. Tractor Design Complexity [From Ref. 7:p. 11]

To illustrate the effect of critical subcomponent reliability on the system, consider Table 2. If 1,000 critical subcomponents, each having a reliability of 99.999%, are arrayed in series, the system reliability is 99.01%. Now if there are 100,000 critical subcomponents, with the same reliability, arrayed in series, the system reliability is reduced to only 36.79%. This figure is even worse if the subcomponent reliability is only 99.0%.

Number of critical components	Individual component reliability			
	99.999%	99.99%	99.9%	99.0%
	System reliability			
10	99.99%	99.90%	99.00%	90.44%
100	99.90%	99.01%	90.48%	36.60%
250	99.75%	97.53%	77.87%	8.11%
500	99.50%	95.12%	60.64%	0.66%
1,000	99.01%	90.48%	36.77%	<0.1%
10,000	90.48%	36.79%	<0.1%	<0.1%
100,000	36.79%	<0.1%	<0.1%	<0.1%
*It is assumed that all critical components are reliabilitywise in series.				

Table 2. Component Reliability and Design Complexity [From Ref. 7:p. 12]

2. The Effect of Reliability on the Logistics Burden and Lifecycle Costs

As the figure below indicates, Operation and Support (O&S) costs can be 72% of the life cycle cost (LCC) of a system. The diagram is somewhat dated, using data from 1980, however, the figures still remain accurate for most programs.

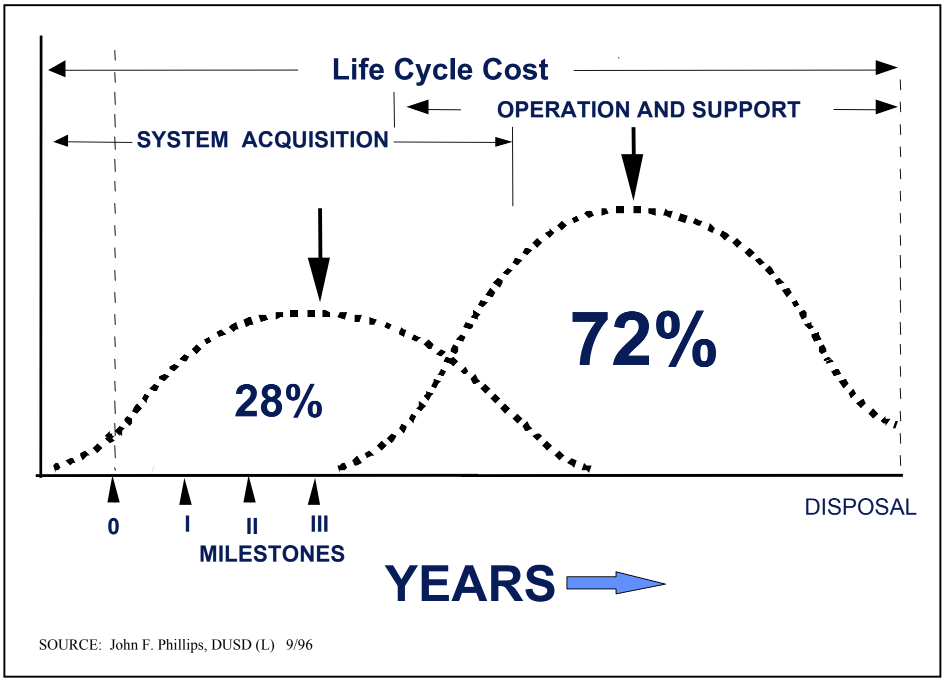

Figure 2. Nominal Cost Distribution (Typical 1980 DoD Acquisition Program with a service life of about 30 years) [From Ref. 7:p. 13-6]

O&S costs are the resources necessary for the operation and support of the system, subsystem, or major component during its useful life. These resources may consist of such things as fuel, spare parts and maintenance, among others.

Managing and reducing O&S costs is a focus of current weapon development programs. Buying into a weapon system may be relatively inexpensive, but operating it and maintaining it can be burdensome. Examining the Army budget supports this statement.

O&S costs are a large part of the Army budget, accounting for almost 33% of the entire budget. By reducing O&S costs, the Army would be able to spend money on more critical needs, such as force modernization or quality of life. O&S costs are also rising partially as a result of less reliable equipment. For fiscal year 2002, the Army requested $26.7B for Operation and Maintenance (also known as O&S), an increase of almost 12% from the previous year.

FY01 vs. FY02 TOTAL OBLIGATION AUTHORITY ($ billions)		
APPROPRIATION	**FY01**	**FY02**
Military Personnel	$28.4	$30.2
Operation and Maintenance	23.9	26.7
Procurement	11.0	11.2
Research, Development, Test and Evaluation (RDT&E)	6.3	6.7
Military Construction	1.3	2.1
Army Family Housing	1.2	1.4
Chemical Demilitarization	1.0	1.2
Base Realignment and Closure	.3	.2
Environmental Restoration	.4	.4
Total *	$73.7	$80.2

Table 3. Army FY01 vs. FY02 Total Obligation Authority [From Ref. 8]

Initial investments in the design and production of reliable weapon systems can have an enormous result by reducing O&S costs. Examples of this are found in the Minuteman I missile system, which estimated that for every dollar invested in the reliability improvement program resulted in a return of eight dollars. Over a ten-year period, the net savings was expected to be $160,000,000. Another example of this savings is that of the Atlas Guidance System. The result of an annual investment of $10,100,000 in a "high" reliability program during

development and production resulted in an annual savings of $58,400,000 after fielding. A last example is of the F-105 weapon system, which, by implementing a reliability improvement program, increased the reliability of the system from 0.7263 to 0.8986, resulting in an annual savings estimated at $25,500,000. [Ref. 7:pp. 23-24]

C. THE FUTURE COMBAT SYSTEMS AND THE NEED FOR ULTRA-RELIABILITY

1. The Future Combat Systems (FCS) Program

The FCS Program is a cooperative development program between the Defense Advanced Research Projects Agency (DARPA), and the United States Army. DARPA, through its Objective Force Program Office (PM-OF), is responsible for the management of the first phase of the system's lifecycle, the Concept and Technology Development Phase.

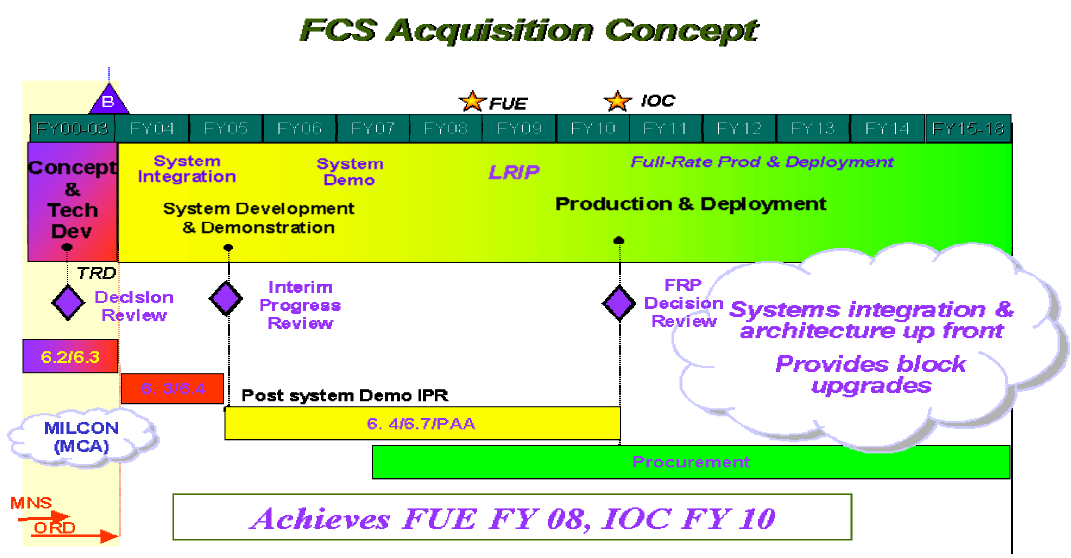

Figure 3. FCS Program Schedule [From Ref. 9]

The Army, through the Future Combat Systems Program Office (PM-FCS), is developing a streamlined acquisition management approach for the program. [Ref. 9]

The purpose of the program is to develop a new, innovative, advanced warfighting capability by incorporating leap-ahead technologies focused on unmanned systems. The program is a Simulation Based Acquisition (SBA), whereby contractors and the Government will utilize modeling and simulation (M&S) to design and develop the force and reduce risk.

FCS is defined as a

> networked systems of systems that will serve as a core building block within all maneuver Unit of Action echelons to develop overmatching combat power, sustainability, agility, and versatility necessary for full spectrum military operations. [Ref. 9]

FCS is envisioned as an ensemble of manned and unmanned systems that will fulfill the ground component requirement of the Army's Objective Force. Key tenets of the FCS are "survivability, lethality, deployability, agility, sustainability, versatility, and responsiveness." [Ref. 9]

FCS will be comprised of "networked space-, air- and ground-based maneuver, maneuver support and sustainment systems." [Ref. 9]

A commonly presented concept is depicted in the figure below. It incorporates both an unmanned aerial vehicle (UAV) and a ground based robotic vehicle that provide reconnaissance, surveillance, and target acquisition (RSTA). A robotic vehicle equipped with missiles provides a beyond line-of-sight (BLOS) indirect fire capability while another robotic vehicle equipped with a main gun provides s line-of-sight (LOS) direct fire capability. A central

command and control vehicle transports the dismount soldiers and provides command, control, communications interface (C3I) for the entire system.

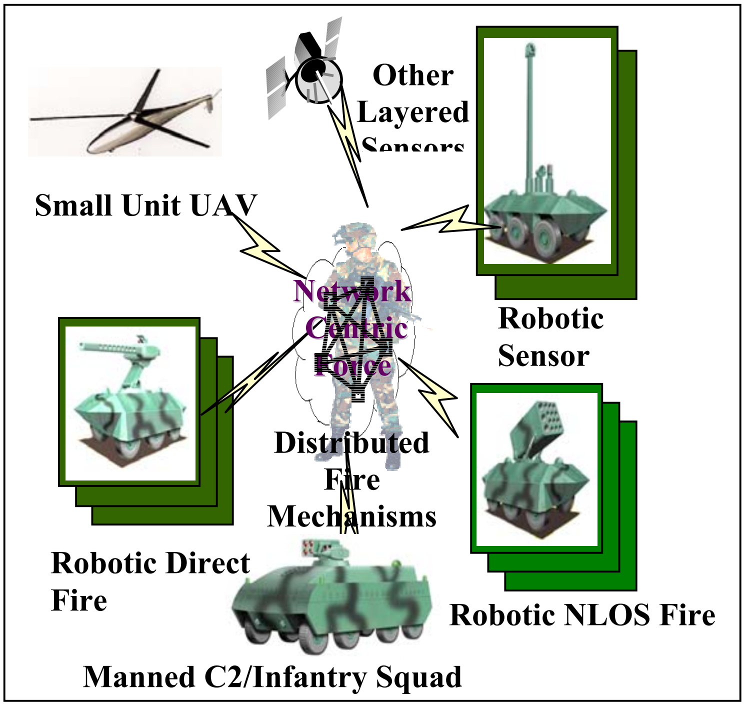

Figure 4. FCS Commonly Presented Concept [From Ref. 10]

2. The need for Ultra-reliability

Because FCS relies on leap-ahead technologies and unmanned, robotic vehicles, reliability is a chief concern of the system. Reliability is also necessary to ensure a reduced logistics burden and acceptable lifecycle costs. For these reasons, the Hon. Paul J. Hoeper, Assistant Secretary of the Army (Acquisition, Logistics and Technology) (ASA(ALT)) requested that the Army Science Board convene a Year 2000 Summer Study to study "Technical and Tactical Opportunities for Revolutionary Advances in Rapidly Deployable Joint Ground Forces in the 2015-2025 Era." [Ref. 11] One focus that the ASA(ALT) requested the board examine was the Sustainment and Support of the future

forces. The goal of this investigation was to identify a sustainment and support capability with a reduced logistics burden, a means to provide future forces with a…

> significantly greater systems reliability … along with graceful degradation and ultra-reliability leading to simplified battlefield maintenance, repair, and diagnostics/prognostics (including disposable / expendable components / systems). [Ref. 11]

The Army Science Board focused on three problems in dealing with FCS Sustainment and Support issues, one of which was the reduction in demand for materiel and support of the FCS. A proposed solution was that the FCS be designed for supportability with a built-in or inherent reliability allowing operation for seven days or more without maintenance and support. Ultimately, the board recommended that the FCS achieve ultra-reliability to reduce the logistics burden. The reason for this recommendation was because ultra-reliability reduces maintenance and support requirements. It reduces the number of maintenance personnel, equipment, and spares required for support. Some estimates indicate that ultra-reliability can reduce service and support personnel requirements in the Objective Force Area of Operations by as much as 83%. [Ref. 12:p. 32]

The Army Science Board further recommended four strategies for achieving ultra-reliability. Tradeoff/payoff analysis using models and simulations is one recommended method for realizing that the benefits of achieving ultra-reliability exceed the costs. A second strategy is the use of prognostics and diagnostics, through

the use of imbedded sensors. This will allow maintenance actions to occur prior to part failure due to failure prediction and analysis. A third strategy is the application of science and engineering principles during system design and development to achieve inherent reliability requirements. The last recommended strategy is the specification of reliability as a Key Performance Parameter (KPP) during procurement and acquisition. [Ref. 12:pp. 42-45]

Ultimately, the board concluded that ultra-reliability should be a KPP for the FCS. However, many senior Defense and Army logisticians, to include the Office of the Deputy Chief of Staff (Operations) (ODCSOPS), Office of the Deputy Chief of Staff (Procurement) (ODCSPRO), ASA(ALT), and the Objective Force Task Force disagreed with this recommendation. The reasons provided for their disagreement are that it is too early in the lifecycle to designate a KPP, it reduces the trade space, and it constrains the Program Manager's flexibility. Only the Headquarters, Army Materiel Command/Army Materiel Systems Analysis Activity (HQ AMC/AMSAA) and the Office of the Deputy Chief of Staff (Logistics) (ODCSLOG) agreed that ultra-reliability should be a KPP. [Ref. 3]

3. FCS Reliability Requirements

The DARPA/Army FCS Program Solicitation, released in November 2001, emphasized the need for reliable systems in the development of the FCS. It recognized that FCS reliability was "critical to reducing [the] logistics foot print and lifecycle cost." [Ref. 9:p. 76]

To achieve this, the solicitation required the FCS have the following reliability capabilities:

> 1. ultra-reliable and/or redundant components to remain operationally effective for the full 3/7-day mission period with minimal pulsed service or repair organic to the Unit of Action. [Ref. 9:p. 76]
>
> 2. reduce demand and minimize the maneuver sustainment burden on unit effectiveness through balanced system reliability, redundancy and repair, to include embedded diagnostics and prognostics as well as modular component design. [Ref. 9:p. 76]

Specified reliability deliverables required the contractor to:

> 1. Propose reliability, maintainability and testability criteria, e.g., confidence levels and no evidence of failure. [Ref. 9:p. 76]
>
> 2. Identify recommended reliability, maintainability and testability criteria to be tested in SDD prototype testing (PQT and LUT). [Ref. 9:p. 76]

D. MANDATORY AND DESCRETIONARY GUIDANCE FOR ACHIEVING RELIABILITY REQUIREMENTS

There are many sources of reliability guidance for the military to assist programs in achieving reliability requirements. The amount of mandatory guidance, however, has decreased as a result of acquisition reform.

This section will present the sources of guidance and the nature of the guidance, whether it is mandatory or discretionary. It will also identify where in the lifecycle of a program the Program Manager should implement the guidance.

1. Mandatory Guidance

There are four mandatory sources of reliability guidance relevant to the Army. Two are Department of Defense Directives, DoDD 5000.1, *The Defense Acquisition System*, and DoD 5000.2-R, *Mandatory Procedures for Major Defense Acquisition Programs (MDAPs) and Major Automated Information System (MAIS)*. Two are mandatory Army Regulations are AR 70-1, *Army Acquisition Policy* and AR 71-9, *Materiel Requirements*. [Ref. 13]

DoDD 5000.1, directs that

> acquisition program managers shall focus on logistics considerations early in the design process to ensure that they deliver reliable systems that can be cost-effectively supported and provide users with the necessary support infrastructure to meet peacetime and wartime readiness requirements. [Ref. 14]

DoD 5000.2-R, directs the PM to

> develop RAM system requirements based on the Operational Requirements Document (ORD) and TOC (Total Ownership Cost) consideration, and state them in quantifiable, operational terms, measurable during development and operational T&E. [Ref. 15]

It further states "reliability requirements shall address mission reliability and logistic reliability." [Ref. 15]

AR 70-1 states

> when reliability and maintainability requirements are included in solicitations, they should be included by specifying:
>
> quantified reliability and maintainability requirements and allowable uncertainties (such as statistical risks),

> failure definitions and thresholds (FDSC), and
>
> life-cycle usage conditions (OMS/MP). [Ref. 16:p. 18]

It further states that

> solicitations should not cite any specification, standard or handbook or include language specifying 'how to' design, manufacture or test for reliability. MIL HBK 217, *Reliability Prediction of Electronic Equipment*, is not to appear in any solicitation as it has been shown to be unreliable and its use can lead to erroneous and misleading reliability predictions. [Ref. 16:p. 19]

AR 70-1, states in paragraph 5-13 Performance-based requirements, "where certain critical processes must be contractually required in order to protect both parties' interest," [Ref. 16:p. 20] in considering program complexity and risk, offerors may be required to first use their own processes, secondly use industry accepted standards, and lastly use Government developed processes to achieve key attributes or performance parameters. Because the objective is to encourage the use of non-Governmental processes, the program manager must obtain a waiver from the Milestone Decision Authority.

In comparison to section 5-8, Defining R&M Requirements, this latitude is not given for achieving R&M requirements. Contractors are instead expected to achieve the requirements on their own.

AR 71-9 directs that

> an effective R&M program that focuses on achievement of operational requirements and O&S cost targets is necessary to ensure that user

> operational reliability requirements will be met. CBTDEVs and TNGDEVs will participate with MATDEVs in defining an effective, tailored R&M program for each system pursued. [Ref. 17:p. 14]

The regulation also goes on to state

> CBTDEV/TNGDEV will provide an operational mode summary/mission profile (OMS/MP) and a failure definition and scoring criteria (FDSC) to support the reliability requirement. [Ref. 17:p. 14]

2. Discretionary Guidance

In addition to the mandatory guidance, there are many discretionary sources of reliability guidance. These discretionary sources consist mostly of Department of the Army Pamphlets and Military Handbooks. Because there are so many, only some of the most relevant sources will be identified.

DA-PAM 70-3, *Army Acquisition Procedures,* devotes an entire section to Reliability, Maintainability and Availability. It provides discretionary guidance concerning establishment of Reliability and Maintainability (R&M) requirements, management, engineering and design, testing, integrated process teams and their assessment. [Ref. 18:pp. 99-105]

There are also several military handbooks that address reliability. These include MIL-HDBK-781A, *Handbook for Reliability Test Methods, Plans, and Environments for Engineering Development, Qualification, and Production,* and MIL-HDBK-189, *Reliability Growth Management.*

MIL-HDBK-781A provides a list of reliability test methods, reliability test plans, and environmental profile data to use as a guide when testing systems for contractual

reliability requirements during developmental testing. The reliability test methods and plans include such things as growth monitoring and MTBF assurance testing. Test environmental profiles are provided for test environments for equipment, vehicles, and aircraft. This testing is necessary to identify defects and failures so they may be corrected prior to fielding. The information contained in the handbook is applicable to all systems and can be tailored for any program. [Ref. 19]

MIL-HDBK-189 outlines reliability growth concepts and methodologies for management of reliability growth during the developmental stage. It first presents the fundamental concepts followed by details for concept implementation. [Ref. 20]

There is not as much regulatory guidance as there has been in the past. Many mandatory standards and specifications have been canceled or made discretionary as a result of acquisition reform.

3. Acquisition Reform and Its Effects

Acquisition Reform has had a great impact on the management of acquisition programs. Key tenants of Acquisition Reform are "better, faster, cheaper." With these objectives, many changes were made to the acquisition process in an attempt to improve the process.

One significant change was the dependence on commercial industry to use their practices and standards in favor of military standards and specifications. This change was made after commercial industry identified military detailed specifications as unnecessary cost drivers. In September 1985, the Under Secretary of Defense

(Acquisition, Logistics & Technology), mandated that the preference for specifications would be first for performance specifications, then commercial specifications, then, as a last resort, for military specifications. [Ref. 21] As a result, many military standards and specifications were revoked, suspended, deleted, or amended.

One mandatory source of reliability management guidance that was canceled was DoD 5000.20, *Reliability and Maintainability*. This directive established policies and responsibility for the reliability and maintainability of defense systems, subsystems, and equipment. It implemented the principles of DoD Directives and Instructions for major system acquisition and for test and evaluation.

Another mandatory source of reliability management guidance that was canceled was MIL-STD-785B, *Reliability Program for Systems and Equipment Development and Production*. This standard was comprised of application requirements, reliability program tasks, and an application matrix that provided guidance and rationale for the selection of tasks. It encouraged task selection tailoring for each program. Selected tasks could be used to

> solicit facts and recommendations from the contractors on the need for, and scope of, the work to be done rather than requiring that a specific task be done in a specific way. [Ref. 22]

It also included increased emphasis on reliability engineering tasks and tests to prevent, detect, and correct "design deficiencies, weak parts, and workmanship defects." [Ref. 22] A discretionary handbook providing this guidance

was to be published, however, the standard was canceled with no superseding document.

E. RELIABILITY AND THE ACQUISITION LIFECYCLE

Reliability requirements are found throughout the acquisition process. This section attempts to outline some of the most important processes involving reliability within the acquisition lifecycle, depicted in the figure below.

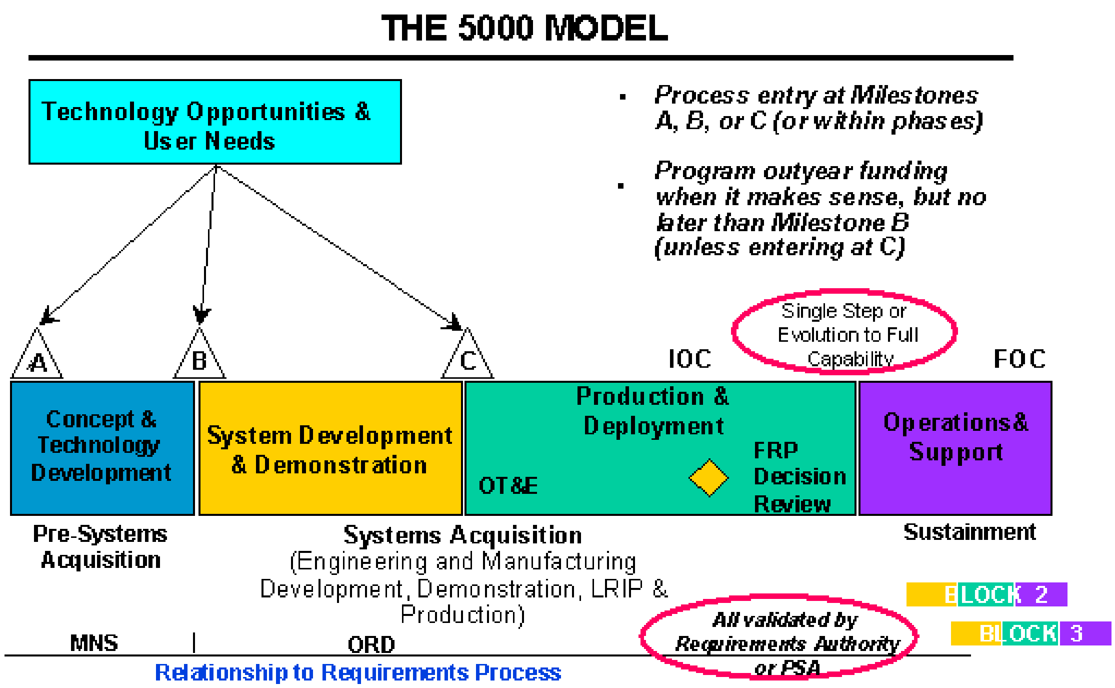

Figure 5. The 5000 Model [From Ref. 23:p. 8]

1. Technology Opportunities & User Needs

This is a pre-acquisition period during which the user needs are developed, and science and technology and concept development efforts are undertaken in the development of a material solution. The user needs are expressed in a Mission Needs Statement (MNS) that is developed in response to a threat. [Ref. 23:p. 9]

2. Concept & Technology Development

Concept & Technology Development is separated by a decision review into Concept Exploration and Component Advanced Development. Concept Exploration is a period of concept studies to define and evaluate alternative concepts. The organization with the mission need conducts an Analysis of Alternatives (AoA) to identify possible system alternatives and their sensitivities to changing assumptions. This gives insight to Key Performance Parameters and their contribution to operational capability. [Ref. 23:p. 13]

Alternatives identified by the AoA are refined through cost-performance tradeoff studies to determine cost drivers for system characteristics. Studies may also determine achievable reliability objectives with respect to cost, schedule, and performance for each alternative. Similarly fielded systems may also be studied to determine operational reliability deficiencies. From these studies, the Combat Developer (CBTDEV), as part of the integrated concept team (ICT), develops system operational requirements, of which reliability should be one. These operational requirements are consolidated in the Operational Requirements Document (ORD) during the requirements generation process. Requirements that are considered critical to the success of the system’s mission are designated as Key Performance Parameters (KPPs). The operational requirements address operational effectiveness (performance oriented), as well as operational suitability (supportability oriented), of which reliability is key. Reliability should be a focus here to ensure that it is not unnecessarily sacrificed or ignored. By designating it as a KPP, reliability will receive the emphasis it requires.

Normally, reliability requirements are stated as a quantitative mission reliability and logistics reliability objective. [Ref. 23:p. 14]

This process leads to the finalization of the ORD and identification of KPPs, the Acquisition Program Baseline (APB), and lifecycle cost estimates.

At the decision review, the Milestone Decision Authority (MDA) selects the preferred concept for development with available technologies. The program then commences to Component Advanced Development.

During the Component Advanced Development period, a concept for the required capability exists, however the architecture is still unknown. When the system architecture has been identified and the component technology has been demonstrated, the program may proceed into the next phase. [Ref. 23:p. 15]

3. System Development and Demonstration

The objective during this phase is to

> develop a system, reduce program risk, ensure operational supportability, design for producibility, ensure affordability, ensure protection of Critical Program Information, and demonstrate system integration, interoperability and utility. [Ref. 23:p. 17]

This is accomplished through the use of simulation-based acquisition and test and evaluation which are guided by a system acquisition strategy and test and evaluation master plan (TEMP).

This phase is divided into two approaches, System Integration and System Demonstration. At entry into System

Integration, a system architecture exists but components have not been integrated into a complete system. When integration has been demonstrated with prototypes and system configuration is documented, the system may enter System Demonstration. During System Demonstration, the system is demonstrated in its operational environment and may enter the next phase if it meets the requirements and commercial capabilities are available. [Ref. 23:p. 17]

During this phase, the system engineering process is used iteratively to translate operational requirements into a system configuration and integrate reliability and other supportability factors to meet cost, schedule, and performance objectives. Reliability Engineers complete analysis such as failure modes, fault tree, and parameter design with designers and other engineers to determine achievability of operational readiness and supportability. Reliability verification through testing programs are also used to verify the design reliability.

4. Production and Deployment

In this phase, the system is approved for Low Rate Initial Production (LRIP) during which a limited number of systems are produced to establish the manufacturing capability. Reliability testing programs are also emplaced to ensure reliability levels are maintained during production. Failure prevention and corrective actions are emplaced to determine product or process improvements. Production representative articles are tested to determine operational effectiveness and suitability during Initial Operational Test and Evaluation (IOT&E) and Live Fire Test and Evaluation (LFT&E). Upon successful completion of

testing, the system is approved for Full Rate Production (FRP) and deployment to the using units. [Ref. 23:p. 23]

5. Operations and Support

Operations and Support is divided into two parts, Sustainment and Disposal. During Sustainment, the system is supported with a program meeting operational support requirements in the most cost-effective manner. During this phase, warranties, such as reliability improvement warranties, may be used to ensure continuous improvement of the fielded system through engineering change proposals to faulty components. Additionally, reliability centered maintenance may be implemented to identify reliability degrading trends and determine root cause. Upon reaching the end of its useful life, the system is disposed of, but not after possible service life extension or rebuild programs. [Ref. 23:p. 27]

F. SUMMARY

High reliability is an important and necessary requirement for weapon system development. It can reduce the logistics burden felt by the services and also reduce lifecycle costs, freeing funds for the procurement of new equipment to modernize the force.

However, its achievement can be elusive for many weapon system programs. The FCS is one weapon system program currently in development that is attempting to achieve high or ultra-reliability to reduce the logistics burden.

Both mandatory and discretionary guidance for establishing and achieving reliability requirements exists, however, there is not as much as there once was. Also,

once mandatory military standards and specifications have been canceled or made discretionary in favor of commercial practices.

Because reliability is encountered throughout the lifecycle, it is necessary to effectively and efficiently manage it. Therefore, an exploratory investigation is necessary to determine what successful programs are doing to achieve reliability requirements.

III. METHODOLOGY

A. INTRODUCTION

This chapter outlines the methodology used for the collection of data. It includes the purpose of the study, the research method, the questions asked, and the selection of study subjects and their description.

B. PURPOSE

The purpose of this exploratory study was to determine what successful programs implemented to achieve reliability requirements given that more than 80% of programs fail. The objective of the study was to identify successful practices, pitfalls, and recommendations for process improvement. The study focused on those successful programs that recently achieved reliability requirements and those people who were intimately involved with the achievement of reliability requirements.

C. EXPLORATORY STUDY

1. Study Overview

The primary objective of the interviews was to identify how successful programs achieved reliability requirements. Programs that were successful in achieving reliability requirements were identified, and a person familiar with the program's reliability requirements was then identified and questioned about program practices.

2. Interview Question Development

Questions evolving from the secondary research questions were developed to determine the successful strategies or practices used by programs to achieve reliability requirements. The focus of these questions was

to identify the program’s organization, how requirements were established, managed, and achieved, and when the program focused on reliability. Additional questions were asked to gather lessons learned and recommendations for improving the process. Lastly, questions were posed to determine if ultra-reliability was achievable and worthwhile. The interview questions are found in Appendix A.

The first series of questions were developed to determine the organization of the programs to achieve their objective requirements. The questions asked how the program was organized for reliability to determine if an Integrated Product Team was used, and who primarily was responsible for reliability issues within the program.

The second series of questions were intended to determine the development of reliability requirements. The questions asked if the program had any input in establishing reliability requirements, how they were determined, and what the requirements according to the Operational Requirements Document were, how they were worded, and how they were conveyed to the contractor.

The third series of questions were developed to determine how the programs managed reliability. The questions asked how the contractor managed reliability growth, and what oversight the program office had. Other questions asked if the program had a Reliability Program Plan, what its key elements were and if their approach was varied. The last question asked what primary sources of reliability guidance were used and if there was adequate guidance.

The fourth series of questions were developed to determine what processes programs used to achieve reliability requirements and how this was measured. The first question asked if reliability was a Key Performance Parameter (KPP) to determine the relative importance. The next questions asked what level of reliability was achieved and how successful the program considered itself and why. The next questions asked how reliability growth was measured, how testing was performed, what the key source of unreliability was, and how developmental reliability figures compared with operational figures. The last questions asked if the contractor was incentivized in any way and how the program planned to maintain the system's reliability once fielded.

The fifth series of questions were developed to determine when, in the acquisition lifecycle, programs focused on reliability. Also asked were some of the most important steps or processes within the acquisition lifecycle.

The sixth series of questions were intended to gather lessons learned, recommendations for improvement, and pitfalls to avoid.

The last series of questions were developed to determine, in the opinion of the subject, if ultra-reliability was achievable and worthwhile.

3. Identification of Study Subjects

Study participants were identified by the Director of Reliability and Maintainability, Army Test and Evaluation Command (ATEC). Selection of the study participants was based on successful or near successful completion of

Operational Testing with respect to reliability. The reason successful programs were chosen is twofold. First, successful programs would better understand how to achieve reliability requirements than unsuccessful programs. Second, successful programs would be more willing to share the reasons for their success. Of the more than 140 programs for which ATEC has visibility, only ten programs were identified as successful. [Ref. 24] These ten programs included: Abrams System Enhancement Program (SEP), Bradley A3, Bradley Fire Support Team (BFIST), M270A1 Launcher, Family of Medium Tactical Vehicles (FMTV), High Mobility Multipurpose Wheeled Vehicle (HMMWV), Aviation Mission Planning System (AMPS), Long Range Advanced Sensor System Suite (LRAS3), Modular Crowd Control Munition (MCCM), and Target Point Illuminator Aiming Light (TPIAL). Of the ten programs, two, the MCCM and TPIAL, had no Reliability Engineers or reliability programs because of the design simplicity and non-developmental nature of the programs, and one, M270A1 Launcher, could not be reached for questionning. After contacting the programs, two more programs were added to the list because of successful reliability achievement. These two programs are Driver's Vision Enhancement (DVE) and Tactical Weapons Sight (TWS). A brief description with reliability requirements and achievements of each of the nine programs questioned follows.

a. Abrams System Enhancement Package (SEP)

Abrams SEP upgrades the M1A2 Abrams tank by adding second-generation thermal sensors, Embedded Battle Command (EBC) command and control software, a Temperature

Management System (TMS), and an Under Armor Auxiliary Power Unit (UAAPU), among others. [Ref. 25]

The Abrams SEP Program conducted Follow-on Operational Test and Evaluation (FOT&E) IV in November 2000. The system had a requirement for 101 Mean Miles Between Failure (MMBF) and demonstrated 511 MMBF. The system also required a combat reliability requirement of 320 MMBF and demonstrated 881 MMBF.

b. Bradley A3

The Bradley A3 integrates the Second Generation Forward Looking Infrared in the Improved Bradley Acquisition System (IBAS) sight and Commander's Independent Viewer (CIV), automated ballistic solutions and target tracking software. [Ref. 26]

The Bradley A3 Program conducted Initial Operational Test and Evaluation (IOT&E) in the fall of 2000. The system had a requirement for 400 Mean Miles Between Failure (MMBF) and demonstrated 417 MMBF.

c. Bradley Fire Support Vehicle (BFIST)

The BFIST integrates the Second Generation Forward Looking InfraRed, Commander's Independent Viewer (CIV), Improved Fire Control, and Fire Support Vehicle Mission Equipment Package onto a Bradley. [Ref. 27]

The BFIST Program had a reliability requirement of 675 MMBF. The program conducted a Production Qualification Test, demonstrating 992 MMBF and a Production Verification Test, demonstrating 1051 MMBF.

d. Family of Medium Tactical Vehicles (FMTV)

The FMTV Program uses a common truck chassis for several vehicle configurations in two payload classes (2.5 ton and 5 ton) and two tactical trailers with complementary payloads. [Ref. 28:p. 281]

The FMTV Program recently underwent Production Verification Testing in January 1999. Reliability requirements and achievements are depicted in the table below.

	Requirement (MMBHMF)	Achievement (MMBHMF)
LMTV Cargo	5500	13333
LMTV Van	4200	6667
LMTV Trailer	2800	20000
MTV Cargo	5500	19048
MTV Tractor	3800	6667
MTV Wrecker	2800	4000
MTV Trailer	2600	20000

Table 4. FMTV Reliability Requirements/Achievements

e. High Mobility Multi-purpose Wheeled Vehicle (HMMWV)

The HMMWV Program is a tri-service program using a light, highly mobile, diesel-powered, four-wheel-drive vehicle with a common chassis for several configurations. A2 improvements include a four-speed, electronic transmission, a 6.5-liter diesel engine, and transportability improvements. [Ref. 28:p. 265]

The HMMWV Program's recent test results are depicted in the table below.

HMMWV Carrier	Requirement (MMBHMF)	Achievement (MMBHMF)
Cargo	1900	4292
TOW/Armament	1800	2937
Shelter	1600	2947
Ambulance	1600	1667

Table 5. HMMWV Reliability Requirements/Achievements

f. Aviation Mission Planning System (AMPS)

AMPS is a Personal Computer based subordinate system of the Army Battle Command System, Maneuver Control System. AMPS facilitates aviation planning functions and automates brigade and below planning and distribution of mission files. [Ref. 29]

AMPS recently underwent Operational Testing in March and April 2001. The system had a requirement for 154 hours Mean Time Between Mission Affecting Failure (MTBMAF) and demonstrated 233.3 hours MTBMAF.

g. Long Range Advanced Scout Surveillance System (LRAS3)

LRAS3 consists of a second generation Forward Looking Infrared with long-range optics, eye-safe laser rangefinder, a day video camera, and a Global Positioning System (GPS) operating in both mounted and dismounted configurations. [Ref. 28:p. 105]

The system had a requirement for 330 hours Mean Time Between Essential Function Failure (MTBEFF) and demonstrated 364 hours MTBEFF.

h. Driver's Vision Enhancement (DVE)

The DVE is a passive, un-cooled thermal-imaging system for drivers of combat and tactical wheeled vehicles.

The sensor module consists of a second-generation Forward Looking Infrared device that delivers a video image to a high-quality, commercial, flat-panel display and control module. [Ref. 30]

The system had a requirement for 740 hours Mean Time Between Operational Mission Failure (MTBOMF) and demonstrated 776 hours MTBOMF.

i. Tactical Weapon Sight (TWS)

The AN/PAS-13 TWS is a family of low-cost, lightweight, infrared imaging devices using second-generation Forward Looking Infrared with medium to high resolution. The system provides a standard video output for training, image transfer or remote viewing and is used for fire control of individual and crew-served weapons. [Ref. 30]

The system had a requirement for 250 hours MTBOMF and demonstrated 3513 hours MTBOMF.

4. Interviews

Interviews were scheduled for the last two weeks of February and the first week of March 2002. Introductory telephone calls were made prior to e-mailing letters of introduction with questionnaire attachments. Appendix B contains a sample e-mail message with a letter of introduction. Study subjects were offered the option to answer the questionnaire by e-mail or by telephone.

D. SUMMARY

The methodology for collecting the data was to identify successful programs and those people within the program who had intimate knowledge of reliability issues. These people were questioned regarding their practices in

achieving reliability requirements, lessons learned, and thoughts on ultra-reliability. The results of the interviews are presented in the next chapter.

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IV. DATA SUMMARY

A. INTRODUCTION

This chapter presents the subjective data gathered from the interviews. Data is summarized, presenting common trends and differences. Questions and responses are grouped by subject area: Organizing for reliability; requirement development; reliability management; reliability achievement; reliability timeline; lessons learned/recommendations for improvement; and ultra-reliability.

B. INTERVIEW RESULTS

A total of seven interviews involving nine programs were conducted as scheduled with two telephonic interviews on 26 February and 4 March 2002, and the remainder by e-mail. Results are presented below. Respondents are not identified to protect anonymity.

1. Organizing for Reliability

The objective of these questions was to determine if programs used dedicated Reliability Integrated Product Teams (IPTs) and who, within the program, was primarily responsible for reliability.

Eight of nine programs stated that the Test Integration Working Group (TIWG) was primarily responsible for developing reliability requirements, while only one program had a Reliability IPT for this. A Reliability, Availability, Maintainability (RAM) integrated working group was incorporated subordinately into the TIWG. This group developed the Failure Definition and Scoring Criteria (FDSC) and "crosswalked and confirmed requirements with the

ORD”. The TIWG was also primarily responsible for developing the test plan for the program. The TIWG was composed of representatives from the test and evaluation community, the material developer, and the user. The TIWG met at least quarterly initially, then more often, usually monthly and bimonthly, just prior to and during tests.

Primary responsibility for reliability within the programs was assigned to a reliability and maintainability branch chief in two cases. In most other programs, a Reliability Engineer, most often provided by matrix support, was responsible for program reliability. Of the few programs that did not have Reliability Engineers, Mechanical Engineers were primarily responsible for reliability. These representatives were most often supported by the TIWG and were members of the RAM scoring and assessment conferences.

2. Requirement Development

The objective of these questions was to determine if programs had influenced requirement establishment.

In all cases, a program reliability representative was able to provide input for establishing reliability requirements. This was most often accomplished through the use of a RAM Rationale Report. The user representative would develop the requirements based on what was considered as the need. The program reliability representative then analyzed the requirement considering “if industry may be able to meet those requirements with [the technology] industry has available today.” If analysis supported the requirement, and it was acceptable to both the user and program representative, it remained unchanged.

Reliability requirements for all programs were primarily based on historical data from similar previous systems, taking into consideration “state of the art and technical feasibility.” In one case, “200,000 miles of historical RAM maturity” data was used. Other methods included “leveraging similar component reliability using other similar programs,” and the “Duane modeling methodology.” In another case, data from the Rome Analysis Center’s, *Reliability Engineer’s Toolkit* and manufacturer’s specifications were also considered in developing requirements.

These requirements, outlined in the previous chapter, were included in contract performance specifications, Acquisition Program Baselines, and Milestone III Exit Criteria. In most cases, the reliability requirements were worded as Mean Miles Between Failure (MMBF) for mechanical systems or Mean Time Between Essential Function Failure (MTBEFF) for electrical systems. In two cases, the reliability requirements from the Operational Requirements Document were expressed in terms of Mean Miles Between Operational Mission Failure (MMBOMF). It was necessary to express these requirements as functions of hardware in terms of Mean Miles Between Hardware Mission Failure (MMBHMF) so that the contractor could be held responsible for sytem performance. To make the conversion between MMBOMF and MMBHMF, a historical “rule of thumb” was used, increasing the operational requirement by one-third to arrive at the system requirement.

3. Reliability Management

The objective of these questions was to determine if programs implemented a Reliability Program Plan.

In two cases, programs began development and testing before implementation of specification reform. This reform prevented specifying 'how to' design, manufacture or test for reliability to contractors. One program stated that the reason for its success was because it was started prior to specification reform.

Another program stated that AR 702-3 was the controlling document for its program. The contractor prepared a RAM design guidebook to be used in all designs and "detailed documentation along with approved contractor program plans allowed for oversight and review of the contractor progress."

One program used "Tiger Teams" of contractor representatives to conduct root cause analysis for "hot issues." Additionally, a Corrective Action Management Review (CAMR), which had representatives from both the program and contractor, periodically conducted reviews to answer systemic reliability issues.

Another program's prime contractor was a Government agency, which already had a proven reliability. Oversight was accomplished through design reviews and configuration control meetings.

Only three programs had Reliability Program Plans prepared for the program office. Two others had plans prepared, which the contractor followed. The remaining programs that didn't have plans, stated that they weren't necessary because of the limited developmental nature of

the program or because of improvement upon a legacy system. One legacy system program had used Reliability Program Plans in the past that included Failure Modes, Effects and Criticality Analysis (FMECA), reliability growth curves, corrective actions systems, and other key metrics.

Of those programs that had Reliability Program Plans, most of the plans were followed closely to ensure the contractor was on the "right track." Some plans may have varied based upon reliability issues such as failures and corrective actions, or to consider value-adding changes.

The primary sources of Government guidance used consisted of both canceled and current publications. The sources included MIL-STD-781 and MIL-HDBK-781, *Reliability Testing for Engineering Development, Qualification, and Production*, MIL-HDBK-189, *Reliability Growth Management*, AR 702-3, *Army Materiel Systems Reliability, Availability, and Maintainability (RAM)*, TRADOC Pamphlet 70-11, *RAM Rationale Handbook*, AR 70-1, *Army Acquisition Policy* and MIL-STD-1629, *Procedures for Performing a Failure Mode, Effects and Criticality Analysis*. Additional information was gathered from other military standards, best practices and meetings with experts in the field.

Some respondents felt there was not enough guidance and "we went from one extreme to the other in specification reform." Another believed it was now necessary to develop reliability policies and ensure they're enforced.

4. Reliability Achievement

The objective of these questions was to determine what processes programs used to achieve reliability requirements and how this was measured.

Reliability requirements were a Key Performance Parameter (KPP) for only one program. In another case, it was stated that reliability exceeded the KPP level and received 4-star (general officer) visibility. The other programs agreed that reliability was important and "essential to fielding an acceptable system to the soldiers".

Two programs rated their reliability achievements (outlined in the previous chapter) as extremely successful because they exceeded their requirement. The reasons stated for their success were due to early establishment of FDSC, well managed scoring conferences, working with the user and RAM community, funded and continuous well managed tests, and an effective failure analysis process as well as processing of Engineering Change Proposals.

Two programs rated themselves as moderately successful because they exceeded the requirement, but were plagued with software or hardware problems.

The remaining five programs rated themselves as average because of difficulty in achieving requirements and also because they are continuing to mature the program. One program indicated its primary reason for success was due to "hard requirements" that had to be met due to the program's visibility. The program also said "top management" must tout the importance of reliability achievement.

The use of design analysis tools or processes for root cause analysis varied by program. One respondent stated that the program "didn't work to influence design" because of the integration of non-developmental items. The program

only relied on the test-fix-test process during the test phase.

One program used Failure Reporting and Corrective Action System (FRACAS) to quickly analyze failures and make corrections. The program used site contractor representatives to provide more timely data than Government systems were capable of.

Another program used a fishbone cause and effect process, FMECA, Sneak Circuit Analysis, fault tree, and component level Environmental Stress Screening (ESS), Highly Accelerated Life Testing (HALT), and Highly Accelerated Stress Testing (HAST) as its primary design analysis tools.

To manage design analysis, three programs created a database to track failures during testing and to conduct root cause analysis with technical engineers from both the Government and contractor.

Both developmental and operational testing played a major role in determining reliability achievement for all programs. All programs used many iterations of test-fix-test during developmental tests prior to operational testing. Three programs also used Limited User Tests as a prelude to Operational Testing. Additionally, due to the maturity of their program, three programs used Production Qualification Tests (PQT) and Production Verification Tests (PVT) to ensure quality and verify the production line.

In comparing reliability figures from Developmental Testing to Operational testing, most programs agreed that there was a reduction due to environment, maintenance, and

“operator induced failures” although in some cases, it was hard to measure, especially when testing software. One program experienced only a 10-15% reduction, while two others experienced a 20-30% reduction.

Key sources of reliability problems were cited as mostly due to hardware, although some software problems were noted. Most hardware problems were a result of the environment due to water and mud infiltration of seals, vibration, and extreme temperature variation. Software was also a problem, and in one case, the “software architecture was not robust and did not lend itself to continuous change and upgrade.”

In only two cases, the contractor was incentivized to achieve reliability requirements. This was not implemented for the entire system, but only for “troublesome components… to assure getting required life with a bonus for life beyond requirements.” Most other programs considered incentivizing the contractor to be unnecessary because the contractor was required to achieve requirements in the contract. For one program, “continuance of the program was the incentive, it either met reliability or there wasn’t a program.”

In planning for maintaining the system’s reliability after fielding, one respondent “hadn’t thought about that.” This respondent believed that once reliability requirements were achieved, it was unnecessary to try to maintain that level unless major engineering changes were made to the system. If engineering changes were made, then it would be necessary to test to check reliability and use the test-fix-test process. It was also thought that because the

operating environment couldn't be controlled, collection of field data was unnecessary and couldn't be incorporated into the program because it was inaccurate. The respondent went on to state that logisticians are more interested in this information and will make appropriate recommendations to the Program Manager for reliability improvement.

Another program uses Original Equipment Manufacturer (OEM) system service representatives at major installations where the system is fielded. These contractor service representatives are similar to Army Materiel Command (AMC) Logistics Assistance Representatives. They "provide technical expertise for correcting problems, locate parts, and suggest engineering change proposals." The difference is that service representatives are specific to only one type of system and are therefore, more knowledgeable, especially for newly fielded systems. They also gather availability data and analyze it for the source of downtime in an attempt to improve it.

Another program used a Field Problem Review board to analyze field data and "decide what problems to investigate, fix, and retrofit in the field." The program would also periodically test a production system to ensure production systems still met reliability requirements.

A similar support plan was used by another program. This program used a System Assessment Management program and Corrective Action Management Reviews (CAMR) to ensure reliability after fielding.

Another program planned to "monitor the system's reliability after fielding via Deficiencies Product Reports (DPR) and Contractor Logistics Support (CLS)."

One last program believed the Army does not adequately "track reliability for systems once they are fielded." The Army maintenance system is not equipped to "capture valuable data that could be used to formulate reliability requirements for future vehicles." "Lessons learned in the field could be applied to current procurements to save time and money in the future."

5. Reliability Timeline

The objective of these questions was to determine when to focus on reliability and what some of the most important steps and processes within the lifecycle were.

All programs began focusing on reliability early in the acquisition lifecycle. Most programs agreed that from "day one," reliability should be a key focus of the program. It was essential for the program to be involved in establishing reliability requirements and getting leadership to "support the reliability program requirements and insure they will be met."

Four programs said that reliability must be a key focus during System Development and Demonstration (SDD) phase of the lifecycle.

Some responses for the most important steps affecting reliability were outlined as beginning with establishing requirements. It is important to ensure "early, accurate analysis of requirements" and that they are "agreed to and understood by all as early as possible." Next was the development of Failure Definition and Scoring Criteria to clearly outline failures for analyzing test results. Followed by steps to influence design using and to predict

or estimate reliability. Lastly, was test-analyze-test to ensure reliability achievement.

6. Lessons Learned/Recommendations for Improvement

The objective of these questions was to identify any lessons learned from the program's attempts to achieve reliability requirements and to also identify recommendations for improvement to the acquisition process regarding reliability.

Responses varied for steps or processes that should be changed. One program indicated the Army maintenance system should be responsible for collecting failure data. This would allow Reliability Engineers to use this data to establish requirements for future components or systems. Similarly, another program thought a more active role was required in component decisions and better planning was needed for availability of spares.

Another program indicated that some specifications and standards should be reinstated which was reinforced by another program that thought the contractor should be required to use reliability data gathered from the field in designing the system. Two programs indicated that the Government should be more stringent in enforcing contractor achievement of reliability requirements.

A last program wanted to "allow probability range on combat mission failures." This program also indicated that the programs should use "technical versus operational testing." It also thought that "participation of the system contractor" should be allowed in operational testing.

Suggestions for other programs to achieve reliability requirements were wide ranging. Most programs did agree that it was necessary to "get management to focus on reliability." A majority of the programs also agreed that it is necessary to ensure effective communications between the program, user, contractor, and RAM community. Other suggestions were to establish a Reliability IPT, "get involved in the reliability program at the beginning," and follow up on the reliability status on a monthly basis. Early, accurate requirements establishment, analysis and traceability and ability to influence design were also important. General consensus existed for establishing detailed Failure Definition and Scoring Criteria to ensure proper assessment of tests. It is also necessary to "test early and often," and effectively analyze and correct failures. For software development, a program suggested use of "open architecture and object oriented design" and use of a Software Engineering Institute (SEI) Capability Maturity Model (CMM) level 3 or higher software design organization.

Common pitfalls to be avoided were varied as well. One program warned against establishing "unrealistic requirements, an unrealistic growth curve based on resources and time," and poor definition of FDSC. One respondent indicated that a lack of communication and support from management must be avoided.

7. Ultra-Reliability

The last series of questions were meant to determine if ultra-reliability should be a Key Performance Parameter (KPP) and if it is achievable.

Responses were mixed regarding whether ultra-reliability should be a KPP. At least one respondent was unfamiliar with the term and would not speculate on its achievability or worth.

Most programs indicated that establishing ultra-reliability as a KPP and achieving it was dependent on the "system, its operating environment, and the use of commercial items."

Mechanically oriented programs were divided regarding ultra-reliability. Two programs thought reliability was an important consideration and may be possible if enough time and money were invested. Two programs indicated that ultra-reliability should not be a KPP for systems such as theirs because it is not realistic or possible for mechanical systems. They stated that ultra-reliability may be possible for "electronics or computer software" but is "not realistic" for "military mechanical systems pounding the cross country terrain at 40 mph" and is therefore, unachievable without exotic materials and unrealistic subsystem redundancy.

Most electronically oriented programs indicated that ultra-reliability should be a KPP because soldiers in the field need reliable systems. One program stated that it should only be considered where "safety is a critical concern." They also thought that it might be achievable if the program had the money and time necessary to invest in its development.

C. SUMMARY

Seven respondents representing nine programs described their successful strategies and practices for achieving

reliability requirements. The viewpoint for the responses was from the perspective of the person most responsible for reliability within the program. The respondents described their approach for organization, requirement development, reliability management, achievement and timeline, lessons learned, and thoughts on ultra-reliability. This information will be analyzed in the next chapter, identifying trends and differences, and comparing these to guidance.

V. DATA ANALYSIS

A. INTRODUCTION

This chapter summarizes the analysis of the subjective data gathered during the interviews of the nine successful programs. Responses were analyzed by subject area, revealing common trends and differences in comparison to published reliability guidance, while identifying advantages and disadvantages of practices.

B. ANALYSIS OF SUBJECT AREAS

1. Organizing for Reliability

DA PAM 70-3 recommends organizing a Reliability Integrated Process Team (IPT) "to review, classify and charge R&M data from system level development and operational tests." Participants of the Reliability IPT are the Program Office or Materiel Developer (MATDEV), the user or Combat Developer (CBTDEV), the Training Developer (TNGDEV), and the independent evaluator. It further states that "R&M IPTs should be held periodically during system level testing" with a final IPT "held at the conclusion of each test." [Ref. 18:p. 103]

Program trends support guidance to the point that a Reliability Availability Maintainability Working Group (RAMWG) was organized subordinate to the Test Integration Working Group (TIWG). This group was responsible for developing reliability requirements and developing Failure Definition and Scoring Criteria (FDSC). The TIWG was comprised of representatives from the test and evaluation community, the material developer and the user. The TIWG

met quarterly initially, then monthly and bimonthly during tests to score test incidents.

An advantage of this organization is that it is an effective way to coordinate testing for reliability. The group is able to easily crosswalk reliability requirements to test plans and scenarios, ensuring test events are scheduled to measure reliability growth. This organization also ensures FDSC are clearly defined. This practice results in efficient scoring conferences due to the prior coordination, definition of failures, and familiarity with test events and incidents.

A disadvantage of this organization is that the group may be focused more on results and on pass/fail testing rather than on influencing design and progressive growth to meet requirements. The subordinate relationship may also diminish the value of the reliability group, making reliability seem less important than testing overall.

The importance of reliability, relative to the individual primarily responsible for its achievement, also varied by program. Most importantly, every program had at least one individual who was primarily responsible for reliability. The level of responsibility varied from program to program. Individual primary responsibility was assigned to a Reliability and Maintainability Branch Chief, a Reliability Engineer, or a Mechanical Engineer in each program. An advantage of assigning reliability to a branch chief is that reliability gains greater importance and has a more powerful advocate. It is also advantageous to have a trained and experienced Reliability Engineer supporting the program. A Reliability Engineer was provided by matrix

support in some programs. An advantage of matrix support is that the person is usually skilled because they work on more than one program and the overhead costs of maintaining that person are reduced because they are shared with the other programs and are not a full-time employee. A disadvantage of matrix support is that the person is not dedicated to only one program and may be working on several at a time. This may result in a lack of complete familiarity with the program that a dedicated program professional may have.

2. Reliability Requirement

AR 70-1 states: "MATDEVs are to participate in the combat or training developer efforts to establish R&M and other system requirements." [Ref. 16:p. 18] DA PAM 70-3 states requirements are determined using the "IPT process… [and] reflect what the MATDEV deems affordable and technically achievable with program funding, risk, and time constraints." [Ref. 18:p. 99]

Program processes are in accordance with documented guidance. In all programs, a program reliability representative was able to provide input for establishing reliability requirements and helped create the RAM Rationale Report. The reliability representatives analyzed and adjusted the user's need considering industrial technological capability.

Advantages of including the program reliability representative in the requirements development process is that the program representative is brought into the system lifecycle at origination and made to feel a member of the team. The representative also better understands the

requirements and the need supporting the requirements. The program representative also provides essential industrial capability information that supports the achievability of requirements. A disadvantage of this process is that it is possible that requirements that exceed industrial capability may be reduced, instead of remaining as an objective to induce industry to achieve and surpass expectations, realizing their full potential.

In developing reliability requirements, all programs used historical data from similar previous systems as a basis for system reliability, adjusted for technological improvements. For components, reliability requirements were developed using three methods. The first method leverages similar component reliability from other programs. The second method uses data from the Rome Analysis Center's, *Reliability Engineer's Toolkit*. The third method was to uses manufacturer's specifications.

Historical information and reliability handbook data can be an excellent source for determining reliability requirements. There is no better source of information than actual performance measurement of similar fielded systems. Care must be taken when adjusting for technological differences because arguments can be made justifying an increase or decrease in reliability. As identified in the modern tractor example in Chapter 2, modern systems are usually more complex in design, which may reduce reliability. However, technological improvement of components can also increase reliability, as the reliability improvements are made to a proven component or

mechanical systems are replaced by more reliable electronic systems.

Using a manufacturer's specifications for reliability requirements is not always an effective method for estimating reliability in military applications. Manufacturers may make claims as to the reliability of their systems, but unless their systems are proven through independent testing or through analysis of field data, claims should be considered unsubstantiated until tested. Manufacturers may also develop specifications from faulty analysis or by using prediction methods for systems unintended for military tactical use. This is demonstrated in the table below, which compares one system's reliability predictions by manufacturers, with MIL-STD-217 predictions for that same system. This comparison resulted in the Government's insistence that MIL-STD-217 not be used as a predictor because of its inaccuracy for field data.

Model	**Predicted Failures Per Million Hours**
Bell Communications Research	12,502
MIL-HDBK-217	715,784
British Telecom	1,258
CNET (French)	16,714
Nippon Telephone and Telegraph	9,525
Note: "MIL-HDBK 217 is not intended to predict field reliability and, in general, does not do a very good job in an absolute sense. The reasons for this are numerous including different failure definitions for field problems that MIL-HDBK-217 does not account for…" RAC Technical Brief, April 1990	

Table 6. Reliability Prediction Comparison [From Ref. 7:p. 10-15]

AR 70-1 states: "Contract R&M requirements should reflect operational R&M requirements in the ORD or reflect

technical values derived from them.” [Ref. 16:p. 100] Programs followed this guidance in translating reliability requirements, outlined in contract performance specifications, for the contractor. In only two programs, reliability requirements varied from those in the ORD. For those two programs, ORD operational reliability requirements expressed in terms of Mean Miles Between Operational Mission Failure (MMBOMF) were translated into hardware reliability requirements expressed in terms of Mean Miles Between Hardware Mission Failure (MMBHMF). Requirements translation was accomplished by multiplying the MMBOMF requirement by 1.33, a widely accepted acceleration, to arrive at the MMBHMF requirement. This translation was done so that the contractor would understand the system reliability requirement independent of operator or maintainer induced failures, and would be responsible for system reliability at the accelerated rate. Using a hardware reliability requirement is acceptable for developmental testing, but during operational testing, the operational reliability requirement must be used. If hardware reliability requirements, instead of operational reliability requirements, were used during operational testing, the contractor could not be held responsible for operator or maintainer induced failures as a result of complex operating, doctrine or maintenance procedures. The only caution is that a sufficient margin of error must be allowed in translating operational reliability requirements to hardware requirements. Additionally, the contractor must be aware of the operational requirement and use Early or Limited User Tests during developmental testing to achieve this with the system design.

To manage reliability and increase visibility, requirements were also included in the Acquisition Program Baseline and Milestone III Exit Criteria. Including requirements in the Milestone III Exit Criteria ensured the Milestone Decision Authority would not approve the system for production or fielding without achieving requirements.

3. Reliability Management

AR 70-1 states: "The MATDEV is responsible for development and implementation of an effective R&M program…." "This applies to all developmental programs and non-developmental item (NDI) programs, other than commercial programs…." [Ref. 16:p. 18]

As a result of specification reform, programs are prevented from specifying to contractors "how to" design, manufacture, or test for reliability. To maintain visibility of reliability achievement over contractors, programs used a variety of methods.

Reviews were one method used to maintain visibility over reliability achievement. A Corrective Action Management Review (CAMR) consisting of both contractor and program representatives worked with "Tiger Teams" of contractor representatives that conducted root cause analysis of failures.

Two programs began development prior to specification reform and, for one of these programs, it was stated as the reason the program succeeded in achieving reliability requirements. Three programs had Reliability Program Plans prepared for the program office, while two other programs had plans prepared that the contractor followed. Four programs stated that Reliability Program Plans were

unnecessary because of the limited developmental nature of the program.

Although these programs were successful in achieving their reliability requirements, they jeopardized their success by not using a Reliability Program Plan. Guidance specifies that implementation of an R&M plan is required for all programs, regardless of their nature. There have been many programs which were thought to be non-developmental or only requiring integration of proven components that instead, proved to be very difficult in achieving reliability thresholds.

Primary sources of reliability guidance according to respondents, consisted of both canceled and current publications. Publications cited included AR 702-3, *Army Materiel Systems Reliability, Availability, and Maintainability (RAM)*, and AR 70-1, *Army Acquisition Policy*, which superseded the currently canceled AR 702-3. Another essential publication included TRADOC Pamphlet 70-11, *RAM Rationale Handbook*, which was also canceled. Cited publications governing reliability achievement included the once mandatory MIL-STD-781 and the discretionary publication that superseded it, MIL-HDBK-781A, *Reliability Testing for Engineering Development, Qualification, and Production*. Additional popular publications were MIL-HDBK-189, *Reliability Growth Management*, and MIL-STD-1629, *Procedures for Performing a Failure Mode, Effects and Criticality Analysis*, which was canceled. According to respondents, many programs still used canceled or superseded Government guidance by transforming that

guidance into performance specifications or directives in the Statement of Work (SOW).

The cancellation of these sources of guidance was primarily due to acquisition and specification reform. A program's inability to specify standards that must be complied with for design, manufacture, or test for reliability can be challenging. With few exceptions, military programs are not allowed to specify standards and task description numbers in contractor's statements of work. Military standards and specifications that were once mandatory were changed to discretionary handbooks as a result of changes made by Government specification reform. These handbooks all have the same forward that states they "cannot be cited as a requirement. If it is, the contractor does not have to comply." These changes were made to allow industry to use commercial standards and specifications instead of stringent Government standards, which were considered as cost drivers and unnecessary.

However, with the cancellation of many military specifications, there is still a void in commercial specifications as some are still awaiting publication. A commercial standard replacement for MIL-STD-785B, *Reliability Program for Systems and Equipment Development and Production*, canceled August 1998, is still awaiting publication by IEEE. This is just one example of this problem. An Internet search for reliability standards and specifications, commercial or otherwise, returns more hits for military standards than any other, even though many have been canceled. It is apparent that commercial industry still looks to the military for providing this

guidance. Another problem with commercial standards and specifications is that many are applicable only for use in commercial environments, not demanding military tactical environments. Military deployments can subject a system to all of the world's temperature or humidity extremes, not to mention dust, vibration and shock.

4. Reliability Achievement

Reliability was designated as a Key Performance Parameter (KPP) for one program while another stated it was more important than a KPP and received general officer visibility. All programs agreed that reliability was an important performance parameter.

Although it may not be necessary to designate reliability as a KPP to successfully achieve reliability requirements, it is necessary to recognize and convey to the contractor the importance of reliability and enforce its achievement. Designating reliability as a KPP would help protect it from trade-offs for seemingly more important considerations such as performance characteristics or decreased initial costs. Only recently have program managers been encouraged to consider system lifecycle costs instead of initial cost that might have permitted buy-ins (inexpensive initial costs with extraordinary operations and support costs).

AR 70-1 states "assessment of R&M in accordance with the FDSC will be an objective in every system level test (technical, operational and production)." [Ref. 16:p. 100] AR 70-1 further states: "A R&M IPT will be held to review, classify and charge test data from system level tests planned for assessment of R&M requirements." [Ref. 16:p.

100] Adherence to this guidance was one reason given for program success. Programs attributed success to early establishment and updating of Failure Definition and Scoring Criteria, well-managed scoring conferences and funded and continuous tests. Failure Definition Scoring Criteria (FDSC) must be clearly defined with consideration of all possible failure scenarios. Failures must be defined with regard to criticality and what constitutes a failure.

AR 70-1 states: "MATDEVs are to plan for and manage system R&M development and are encouraged to utilize reliability growth planning tools." [Ref. 16:p. 99] Some programs implemented this guidance by establishing a database for tracking failures and root cause analyses. Reliability growth tools used by programs included Failure Mode Effects and Criticality Analysis (FMECA), Test-Analyze-Fix-Test (TAFT), fishbone cause and effect, Failure Reporting and Corrective Action System (FRACAS), and component level Environmental Stress Screening (ESS), Highly Accelerated Life Testing (HALT) and Highly Accelerated Stress Testing (HAST). Although these are all good reliability growth tools that work to identify causes for failure, these tools are primarily reactive to failures instead of being proactive, and working to prevent failures. One tool, FMECA, does attempt to influence design by analyzing potential system failures. No programs indicated the use of Physics of Failure (PoF), a reliability design tool that uses Modeling & Simulation (M&S) to "identify first-order failure mechanisms prior to physical testing." [Ref. 4:p. 10-16] One program stated that it "didn't work to influence design" because it was

merely integrating non-developmental items. Reactive tools may be effective when used in this situation, but developmental programs cannot wait until after the design is established to measure reliability and could benefit from use of a predictive modeling tool to evaluate trade-offs and assist in design.

Incentivizing a contractor can be effective for achieving and exceeding reliability requirements. However, only two programs incentivized their contractor for troublesome components. Others stated that there was no need to do this because the contractor knew what had to be done and continuing the program was incentive enough.

Regarding reliability sustainment after fielding, one program hadn't thought about it and stated that the logisticians were primarily concerned with that. Other programs planned on using service representatives and review boards to identify and correct failures. Another program would use Deficiency Product Reports (DPR) and Contractor Logistics Support (CLS). One last program thought the Army could do a better job of tracking parts and system reliability to better improve faulty components.

The comment by one program Reliability Engineer that it hadn't considered reliability after fielding and it was the responsibility of the logisticians is disconcerting. This comment is equivalent to a asking a production line worker "Who is responsible for Quality Assurance/Control?" and getting the response, "They are, down there." Reliability at all stages should be a concern of everyone within the program. Logisticians, as well as Reliability

Engineers, should be concerned with it from the beginning to effectively plan for support.

5. Reliability Timeline

All programs agreed that it is necessary to focus on reliability early in the lifecycle. Helping to establish reliability requirements that are "agreed to and understood by all" is one of the most important steps in the process. These reliability requirements can mean success or failure for a program. If requirements aren't considered to be optimal for all stakeholders, then there is a chance that "requirements creep" can occur. This creep or change of requirements can cause a program to spend additional time or money in attempts to meet increasing requirements, or to needlessly spend time and money trying to achieve a requirement that is later deemed unrealistic and then reduced.

The next important step is to establish Failure Definition and Scoring Criteria (FDSC) that are easily interpreted and understood by all. If FDSC do not clearly outline what constitutes a failure, much time can be spent arguing for one interpretation or another. Failure definitions are prepared for all possible eventualities to ensure that failures are recognized and properly scored.

In designing the system, it is important to influence the design to increase reliability by using a design analysis tool such as PoF. Poorly planned designs can greatly increase system lifecycle costs. This is because once a design is established, future program costs are often more than 70% established. [Ref. 4:p. 12-5]

Last is the test-analyze-fix-test (TAFT) process. This process tests the component or system, analyzes failures, fixes the failures and retests to ensure the failure was corrected and other failures didn't occur as a result of the fix. Testing is an important step and must occur throughout the system's lifecycle. Developmental testing is important to reduce risk and confirm specifications. Operational tests determine if the system is operationally effective and suitable.

6. Ultra-reliability

Most survey respondents were unfamiliar with the term ultra-reliability or had no experience in attempts to achieve it. Respondents did agree that designating ultra-reliability as a KPP depended on its achievability and on the system, the operating environment, and use of commercial items. Mechanical systems programs believed that ultra-reliability goals were unachievable for their systems due to the demanding operating environment. Electronic system programs believed it was achievable if sufficient time and money were available.

Ultra-reliability is considered a means for reducing the logistics burden and decreasing lifecycle costs, but the recommendation for designating ultra-reliability as a KPP met resistance from some high ranking Army officials who argued that it was too soon in the lifecycle to do this, and it would also reduce trade space. If ultra-reliability is not established as a KPP at the start of the program, then later might be too late to try to achieve it due to the necessity to design in ultra-reliability from the beginning. "Key trade-offs between [components]… and

design layout occur early in a program and can significantly impact the reliability and lifecycle costs of a system." [Ref. 31]

Modeling and Simulation tools, such as Physics of Failure, exist for development of systems with ultra-reliability and some systems, such as the Space Shuttle, are working to achieve it. It's true that it requires a substantial initial investment, however, the benefits, such as reduced O&S costs and lives saved, will make a valuable but intangible return on the initial investment many times over.

C. SUMMARY

Analysis of the interview data shows that there are many successful practices and strategies in use. Some of these practices support documented guidance, while others are independent of guidance.

Successful programs treated reliability as an important goal and enjoyed the support of management. They were sure to focus on reliability from the beginning and continued to mature it through definition of requirements, measures, analysis, and testing, fixing and retesting.

Programs identified that tracking reliability for fielded systems and components for their own use as well as other programs using similar components and systems could be improved. Programs also stated that the Government must reinstate or publish more mandatory reliability guidance to better manage its achievement.

As for ultra-reliability, most mechanical programs believed it wasn't applicable to their types of systems and wouldn't be achievable without an extraordinary investment

of time and money. Electronic programs thought it could be achieved, but should only be considered for safety critical components or systems.

VI. CONCLUSIONS AND RECOMMENDATIONS

A. INTRODUCTION

Because only 20% of Army weapon system programs meet reliability requirements, it is essential to capture successful strategies and practices. Analysis of the subjective questionnaire data gathered and presented in the previous chapter reveals many interesting practices used by the few successful programs to achieve reliability requirements. In this chapter, conclusions are drawn regarding successful practices and recommendations are made for implementation of these practices for programs attempting to achieve reliability requirements.

B. RESTATEMENT OF RESEARCH QUESTIONS

Preliminary research questions are addressed here with a short summary of the answer.

- **What is reliability and how does it affect total life cycle costs and the logistics burden?**

Reliability is "the probability that an item will perform its intended function for a specified interval under stated conditions." [Ref. 2:p. 36] Generally, reliability is most often modeled as an exponential distribution that is a function of MTBF and time, and as time increases, reliability decreases.

An investment of one dollar in reliability was proven to decrease lifecycle costs by eight dollars in one case and five dollars in another case. With this savings, funds may be redirected to more pressing needs such as modernizing the force or quality of life improvement.

Reliability has the effect of reducing the logistics burden. More reliable systems require less spares and maintenance, reducing the logistics footprint on the battlefield.

- **What is ultra-reliability and why is this a recommended goal of FCS?**

Ultra-reliability is recognized as an extremely high level of reliability, however, there is no standard numerical reliability figure or definition associated with it. The National Aeronautic Space Administration (NASA) refers to ultra-reliability in software as having a failure probability during a one-hour test mission of less than 0.0000001. This means that the software will not fail 99.99999% of the time. [Ref. 4]

The Army Science Board recommended that ultra-reliability be a goal of the FCS because it will reduce the logistics burden by decreasing the number of maintenance personnel, equipment, and spares required for support. Some estimates indicate that ultra-reliability can reduce service and support personnel requirements in the Objective Force Area of Operations by as much as 83%. [Ref. 12]

- **What is the guidance for achieving reliability requirements?**

Both mandatory and discretionary guidance exists for the achievement of reliability requirements, but, because of acquisition reform, there is not as much mandatory guidance as there once was.

Limited mandatory guidance for achieving reliability requirements for all services is provided in DoDD 5000.1

and DoD 5000.2-R. Army specific mandatory guidance is found in both AR 70-1 and AR 71-9.

There are many discretionary sources of reliability guidance in addition to the mandatory guidance. Discretionary sources consist mostly of Department of the Army Pamphlets and Military Handbooks. Some of the most important and management relevant guidance is found in DA-PAM 70-3 which devotes an entire section to Reliability, Maintainability and Availability. There are also several military handbooks addressing reliability including MIL-HDBK-781A and MIL-HDBK-189.

There is not as much regulatory guidance as there had been in the past. Many mandatory standards and specifications have been canceled or made discretionary as a result of acquisition reform in the interest of eliminating cost drivers and giving preference to commercial standards over military standards.

C. CONCLUSIONS AND RECOMMENDATIONS

The primary research question of this thesis is:

What strategies should be used to achieve reliability requirements for weapon system development?

1. Strategies of Successful Programs

Secondary research questions supporting this question focused on:

How have successful weapon system programs achieved reliability requirements?

To answer this question, nine successful programs were questioned regarding their practices.

a. Organizing for Reliability

How did programs organize to achieve reliability requirements?

Conclusion: Most programs organized Reliability Working Groups subordinately to the Test Integrated Working Group (TIWG). A person primarily designated for reliability, usually a Reliability Engineer, represented the program in the groups.

Recommendation: Programs should organize a Reliability Integrated Process Team to identify, solve, and manage reliability issues. Instead of working subordinately for the TIWG, this group should have equivalent authority, while also working with the TIWG to coordinate testing.

b. Requirements Development

How were reliability requirements developed?

Conclusion: Reliability requirements were developed with input from both the user and program reliability representative based upon need, industrial capability, technological advancements, and historical information. The collection of historical information for use by programs should be vastly improved. When defining reliability requirements, only one program designated it as a Key Performance Parameter (KPP), but all other programs treated reliability as an important objective.

Recommendation: Programs should develop a Reliability, Availability & Maintainability (RAM) Rationale Report using an Integrated Product Team (IPT) process based upon historical information for similar systems and components with consideration given to industrial capability and technological improvements. To prevent the

possibility of requirements being reduced due to a lack of technological capability, the requirement should remain as the objective with the technological capability as the threshold. The contractor could then be incentivized to achieve the objective requirement.

The Standard Army Maintenance System and maintenance practices should be modified to enable the collection of reliability data for components as well as systems. Pertinent necessary information, at a minimum, that should be collected includes hours or miles operated. For depot level reparables, an analysis of the reason for failure, performed by the repair technician, should also complement the operating time. The collected information could then be provided to the program office to design decisions impacting reliability issues.

Programs should also designate reliability as a KPP for programs that are electronic in nature and where safety or system criticality is a primary concern. If reliability is given the same weight as performance, cost, and other factors during the trade-off process, it should not be unnecessarily sacrificed.

c. Reliability Management Plans

What management plans for achieving reliability requirements were developed and implemented?

<u>Conclusion:</u> Most programs did not have Reliability Program Plans because of the limited developmental nature of their systems. Programs managed reliability achievement through RIWGs that analyzed and scored test data. Teams of contractor and program

representatives conducted root cause analysis to identify and correct failures.

Recommendation: Programs, especially developmental ones, should develop and implement Reliability Program Plans to effectively manage reliability achievement. Key aspects of the Reliability Program Plan should be: organizational responsibilities; requirements development; Failure Definition and Scoring Criteria; use of design tools such as Physics of Failure; test plans; root cause analysis methods; and incentivizing for achievement.

d. Reliability Achievement

What processes were used to achieve reliability requirements and how was this measured?

Conclusion: Primarily, a test-analyze-fix-test process, which encourages reliability growth, was used to achieve reliability requirements. Reliability requirements were measured and analyzed during developmental testing. Many programs didn't attempt to design in reliability prior to testing because they were not developmental programs. Developmental programs would benefit from a design analysis tool such as Physics of Failure to develop the optimal design prior to commitment of funds for an unproven design. Non-Developmental Item (NDI) programs with significant integration challenges could benefit as well.

Contractors were incentivized to achieve reliability requirements for troublesome components. It is not necessary to incentivize a contractor for the entire system, as this could be very costly. Nor should a contractor be incentivized from the start, as it would be

difficult to determine what the most troublesome components would be and to determine how much of an incentive should be used.

Reliability Engineers must be concerned with reliability throughout the system's life instead of just focusing on "getting through testing." Reliability Engineers must work with and assist logisticians, even after the system is fielded. This should be a result of the Reliability IPT process, instead of compartmentalized planning and development.

Recommendation: Programs should use many iterations of developmental testing to measure and "grow" reliability using the test-analyze-fix-test process. Programs should also use Physics of Failure to design in reliability prior to testing to reduce the number of costly iterations. Incentives should be focused on troublesome components, rewarding the contractor when requirements are exceeded. Reliability Engineers should work closely with logisticians as part of an IPT, to better coordinate logistics planning and influence reliability after fielding.

e. Reliability Timeline

Where in the Acquisition Process was the program focused on achievement of reliability requirements?

Conclusion: All programs agreed that reliability must be a key focus from the start of the program. It's important to first define reliability requirements that are acceptable to both the user and program, define Failure Definition and Scoring Criteria (FDSC) to allocate failures

and score them, and to use an iterative test-analyze-fix-test process to achieve reliability growth.

Recommendation: Programs must focus on reliability early in the lifecycle before final development of the Operational Requirements Document (ORD).

2. Ultra-reliability

Should ultra-reliability be a goal of weapon system programs?

Conclusion: Most programs agreed that ultra-reliability is a difficult objective to achieve because of the immense investment of time and money.

Recommendation: Ultra-reliability should only be implemented in those programs where a cost-benefit analysis demonstrates that the benefits of achieving this difficult objective outweigh the costs. Consideration must be given to the technological risk and should only be pursued for electronics systems or critical safety related items.

3. Application of Successful Strategies

What are the best strategies that should be used for the Future Combat Systems (FCS) Program as well as other weapon system programs?

Conclusion: The FCS is a program that could be compared to a combination of the previously discussed programs. It has elements of each of these programs in that it is a program, in the developmental stage, relying heavily on mechanical, electrical, and software systems.

Recommendation: The FCS program, as well as other programs, should implement the previous recommendations to achieve reliability requirements.

D. LESSONS LEARNED/RECOMMENDATIONS FOR IMPROVEMENT

Much can be learned from successful programs. *The Acquisition Logistics Guide* outlines many successful reliability practices used by organizations in its Reliability and Maintainability chapter. Interviewed programs also made good recommendations for changing steps and processes concerning reliability achievement.

AR 70-1 states: "MATDEVs are to track fielded systems failure and repair histories starting at First Unit Equipped (FUE)." [Ref. 16:p. 99] One program stated that this could be improved upon. A recommendation made for process improvement was for the Army maintenance system to be held responsible for collecting reliability failure data for components in service. The benefits of this recommendation are that the programs responsible for these systems and components would gain better visibility of failures, their causes, and recommendations for improvement. Other programs could also benefit by having field reliability data that could be used for comparison, estimation of future requirements, and even selection of contractors and components. Currently, programs only have visibility of parts requirements or demand trends without knowing the length of time the part operated, operating conditions, and reasons for failure. LARs at the installation level may sometimes investigate and report failure trends identified in the field. If programs are notified or aware of failures, they may also investigate causes and if correctable, initiate engineering change proposals. Reliability Centered Maintenance programs have also been used to develop a scheduled maintenance program

to identify and prevent failures by replacing parts before it affects system readiness.

Programs also stated that there was not enough guidance concerning reliability management and achievement. They thought that the Government had gone too far in canceling many military specifications and standards and that some should be reinstated.

Another idea by one program for a process change would be to allow "participation of the system contractor" in operational testing. Law prohibits contractors from participating in operational testing to prevent them from taking measures to ensure the system passes. The reason for this is to ensure they don't try to step in to correct failures or other problems prior to completion of the test, altering the test conditions, and preventing a true measure of the system's performance. However, one program found that contractors could observe problems during testing as they occurred without making corrections, so that they better understood the problems and failures and their ramifications. By doing this, contractors knew what changes to make to allow the system to successfully complete testing at a later date.

E. RECOMMENDATIONS FOR FURTHER STUDY

The scope of this thesis dealt only with successful Army programs that had recently and successfully completed testing with respect to reliability. This researcher did not consider other services or civilian organizations because the researcher was primarily interested in Army programs and the environment in which they operated.

Recommendations for further study include:

1. A comparison of the practices of the Army with other services and civilian organizations in achieving reliability requirements.

2. A study of the methods that the National Aeronautic Space Administration uses to achieve reliability requirements, focusing especially on ultra-reliability.

3. The perspective of the civilian contractor counterpart in achieving reliability requirements.

4. A study comparing reliability predictions, measurements from testing, and actual field data to determine the effectiveness of the predictions and testing.

F. THESIS SUMMARY

Reducing the logistics burden is a current focus for the Army as it works to develop and field the Objective Force. Increasing reliability is a key method of achieving this goal, with an added benefit of reducing O&S costs.

Many programs are struggling to achieve even half of their established reliability requirement. Therefore, we should look to successful programs to show us the way in achieving requirements. If we are unsuccessful in our endeavors, future forces will be unnecessarily burdened by our mistakes and incapable of progress.

The Army aviation community is currently experiencing the effects of attempting to manage this problem by maintaining an aging fleet. COL Stephen Mundt, aviation director in the office of the Army's deputy chief of staff for programs concluded "maintenance and readiness issues in our aviation fleet render our current aviation force unaffordable." [Ref. 32] Further, the aviation branch is

questioning its ability to support the future Objective Force because of modernization difficulties as a result of budget limitations.

If we are to transition to and field an effective Objective Force and other future forces, we must be successful in improving reliability in systems under development. Otherwise, our mistakes will degrade our effectiveness and decrease our capabilities for years to come.

APPENDIX A. INTERVIEW SUBJECT QUESTIONNAIRE

This appendix contains a copy of the interview questionnaire that was administered to the study subjects.

Successful Strategies for Achieving Reliability Requirements Questionnaire

Name:
Job Title:
Organization:
Life Cycle Phase of Program:
Program ACAT Level:
Date of OT:

1. Organizing for Reliability
a. How was your program organized for reliability (e.g., was there a reliability IPT, who was represented, what was their purpose, and how often did you meet)?

b. Who within the program was primarily responsible for reliability (e.g., was there one person or more and what was their job title and job description)?

2. Requirement Development
a. How much, if any input did you have in establishing reliability requirements?

b. How were reliability requirements determined (e.g., were they based on historical information, derived goals, or another method)?

c. What was your requirement for reliability, how was it worded by both the user and to the contractor, and in what documents was it specified to the contractor?

3. Reliability Management
a. Because AR 70-1, Army Acquisition Policy, directs that solicitations should not specify 'how to' design, manufacture or test for reliability, how did the contractor manage reliability growth and achievement and what oversight did you have over the contractor's methods.

b. Did you have a Reliability Program Plan, and if so, did you use a documented template, and what were its key elements?

c. How much of the plan did you follow? Did you vary your approach?

d. What were your primary sources of reliability guidance and do you feel that there is adequate amount of guidance regarding reliability, why or why not?

4. Reliability Achievement

a. Was your reliability requirement a Key Performance Parameter (KPP) and if not, how much emphasis did its achievement receive?

b. What reliability did you actually achieve?

c. How would you rate your program's achievement of reliability requirements (extremely successful, moderately successful, or average) and why do you rate yourself at that level?

d. To what do you attribute your success, and did you do something that you feel is innovative or extraordinary?

e. What design analysis tools or process did you primarily use, and why, for failure root cause analysis?

f. What role did testing play in achieving reliability requirements and how much and what types were conducted?

g. When comparing the reliability figure measured in Operational Testing to that from Developmental Testing or estimates, roughly what percent of an increase or decrease was experienced and to what do you attribute the change?

h. What were the key sources of unreliability (i.e. was it hardware or software, what was its function, and why was it so troublesome)?

i. Did you incentivize the contractor in any way to achieve reliability requirements, why or why not?

j. How do you plan to continue to maintain the system's reliability over time after fielding?

5. Reliability Timeline

a. When did you begin focusing on reliability (i.e., at what phase or step in the acquisition life cycle) and why was it important to be involved at that time)?

b. What are some of the most important steps by phase affecting reliability in the acquisition life cycle that must be accomplished?

6. Lessons Learned/Recommendations for Improvement

a. If you had the power to change any step, requirement, or process for reliability achievement, what would you change and why?

b. What are some suggestions that you would like to pass to any program attempting to achieve requirements? (Please provide at least three)

c. What are some of the common pitfalls to be avoided?

7. Ultra-Reliability

a. Should ultra-reliability be a KPP for weapon system programs, why or why not?

b. Is ultra-reliability achievable in the current environment and is it worthwhile, why or why not?

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APPENDIX B. LETTER OF INTRODUCTION

Dear Sir:

Your program was identified by ATEC as an exemplary organization for the achievement of reliability requirements as measured by Operational Testing.

I am completing my Master degree thesis at the Naval Postgraduate School in Monterey, CA. The title of my thesis is, "Successful Strategies for Achieving Reliability Requirements in Weapon Systems Acquisition." I expect to graduate in March, so time is of the essence in gathering my data.

Therefore, I am conducting a survey regarding your successful achievement of reliability requirements to explore your command/agency's strategies and methodology. Because you are one of only five exemplary programs, it is essential that you are as detailed as possible when answering the questions to fully capture your strategies.

My seven areas of interest concern: 1) organization; 2) requirements development; 3) reliability management; 4) measures of achievement; 5) where in the acquisition lifecycle you focused your efforts; 6) lessons learned; and 7) your thoughts on ultra-reliability. I believe that many programs could benefit from your practices, as many are struggling with achievement of reliability requirements.

Please respond to the attached questionnaire by opening it, filling in responses after each question, and saving it, then attaching it to an email and return it by **Friday, February 22**. If you have any questions regarding the questionnaire, please email me. If you would prefer to conduct a telephonic interview using the provided questions, I would be happy to give you a call in the next week at your convenience. Please let me know when I should call by emailing me at jmthorne@nps.navy.mil <mailto:jmthorne@nps.navy.mil>, or leave a voice message at (831) 899-8614.

I will summarize all input responses in the analysis of data. If you desire, I can forward a finished copy of my findings.

I thank you for your assistance and with the immediate response.

questionnaire3.dot

Sincerely,
CPT Jim Thorne
Army Acquisition Corps

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